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16. ABSTRACT

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WATER DISTRIBUTION SYSTEMS: A SPATIAL AND COST EVALUATION

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ABSTRACT: Problems associated with maintaining and replacing water supply distribution systems are reviewed. Some of these problems are associated with public health, economic and spatial development of the community, and costs of repair and replacement of system components. A repair frequency analysis has been completed for distribution system maintenance events (leaks and breaks). The economic implication of various replacement strategies and the effect of water quality (corrosivity) on water loss and system cost are examined. This analysis is based on the data acquired from one large (260 mgd; 11.39 m^3/s) and one smaller (20 mgd; 0.88 m^3/s) water utility. As this study shows, once a length of pipe begins to require maintenance, its maintenance rate increases exponentially. Maintenance costs soon exceed the costs of replacement. Therefore establishing a timely maintenance and replacement program is extremely important from an economic and public health viewpoint.

INTRODUCTION

The treatment and delivery functions of a water utility represent large economic investments, but the bulk of the expenditures are in the delivery system. The absolute magnitude of this expenditure can be illustrated from data taken at a large midwestern water utility (approx 260 mgd (11.39 m^3/s) capacity) which is examined in detail in Ref. 1. The replacement value of the delivery system (not including treatment, acquisition, and support services) is estimated at $917,814,700 based on current dollar/foot rates (1978). Maintenance of the delivery system in 1978, cost approx $2,600,000 per year.

Not only does the water utility delivery system represent a large and important portion of the water utility's budget, but it also plays a significant role in community public health and can become a determinant of the communities growth path. The research resulting from this study will deal with two major issues related to water supply systems. The first is the interaction between land use and

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development and water supply system development, and the second is the cost and frequency of water system network replacement.

Design Characteristics of the Distribution System

Design of water distribution systems can be divided into four major areas. The first is concerned with basic land use and demographic parameters used to determine the preliminary size and shape of the service area. The second area of concern reflects the natural features of the service area. The third area of concern is the capacity requirement of the system as a whole and that of individual components. The fourth area of concern is that of engineering design criteria, such as the diameter of pipe, the minimum and maximum velocities, minimum and maximum slopes, and the flow characteristics of the pipes themselves (11). Table 1 summarizes these major areas of consideration.

Case Study Utilities

Two utilities were used as the source of data for this report. The larger utility serves a population of nearly 3/4 million and, until recently, derived all of its water from one source. The larger utility has a maximum capacity of nearly 260 mgd (11.39 m^3/s). On a yearly average, approx 150 million gallons of water are pumped per day (6.51 m^3/s). The distribution system is made up of 3,900 mile (6,275 km) of mains, 97.5% of which are cast iron, 2.1% are reinforced concrete pipe, and less then 1% are steel.

The smaller utility located near the larger utility serves a combination of rural and urban users and also draws water from two sources. Treatment in 1979 yielded 6.7 billion gal of water (25.4 billion L). Most of the 360 mile (579.2 km) of pipe are cast iron; the remainder are reinforced concrete or steel.

Analysis of System Reliability.—Facilities used for supplying water service, although predominantly of a more permanant character than those of other public

TABLE 1.—Parameters of Distribution System Design (11)

Criteria for distribution system design (1)	Physical design consideration (2)
Basic land use/demographic parameters	service area, land use, densities, population growth
Natural features	topography (slopes), soil types, water table
Capacity requirements	per capita flow, peak-to-average flow
Engineering design criteria	pipe characteristics: Manning's n
	joint materials
	minimum pipe diameter
	minimum velocity
	maximum velocity
	minimum and maximum slopes

utilities, are nevertheless subject to mortality and replacement. Because facility life is long, great difficulties arise in securing factual data relating to actual life and mortality experience. Even before a pipe reaches the point of ultimate replacement, as it ages, its carrying capacity is severely reduced. Many cities are experiencing high maintenance rates, indicating that their distribution systems are failing (12,7,6).

As mentioned earlier, water main breaks disrupt service, reduce fire fighting capacity, may damage property, and pose a public health threat while incurring substantial repair and replacement costs. When a pipe breaks, the leak has to be located, the pipe excavated, and the leak fixed or a section replaced. A section of pipe experiencing a significant number of breaks or leaks, may be replaced entirely with a new pipe (10).

The reasons for breaks are in the following categories: (1) Quality and age of the pipe itself, including connectors and other equipment; (2) type of environment in which the pipe is laid, e.g., the corrosiveness of the soil, frost and heaving, and external loads; (3) quality of the workmanship used in laying the pipe; and (4) service conditions, such as pressure and water hammer.

An analysis of water main breaks can provide insight into the reasons breaks are occurring in a given area of the network or in a specific pipe. Insights from such an analysis can change pipeline design and construction policies and provide information as to whether or not a pipe should be repaired or replaced. In deciding whether to replace a pipe, the replacement cost and future costs associated with the new line should be compared with the cost of repairing the existing line and incurring possible future costs of repair and disruption of service.

During the course of this analysis, the investigators found the definition of "break" to be difficult to establish. Examination of many years of data revealed that few actual "breaks" occurred; a "break" in this context is a rupture of the line causing a cessation of service. A more subtle and insidious occurrence was continuous leakage from certain pipes causing maintenance crews to take remedial action. Therefore, the analysis contained in this report is based on "maintenance events" or repairs but not on actual ruptures. A repair is defined as any event in which water was leaking and to which a crew was dispatched. These events do not include leaks from valves or clamps, but only joint or main line leaks. Valves and clamps were considered to be either internal or external fixtures but not part of the pipe itself.

Many factors were found to influence the number of maintenance events associated with a given pipe. The following sections contain an analysis of some of these factors and an economic evaluation of the optimal time for pipe replacement.

Analysis of Maintenance Event Data.—Common sense and experience would indicate that there are many variables that might influence repair events. The basis for this study is a data set from the two case study water utilities consisting mostly of feeder and transmission mains. The data set includes the pipe lengths considered in the analysis, associated physical design and demographic data, and cost data. These mains have been categorized into 457 separate pipes. Separation into pipe links was based on a junction between pipes or a change in pipe diameter. No pipes laid before 1940 were used in the analysis. Break data for smaller pipes were virtually nonexistent.

The following data were collected for each pipe section: diameter; material; age; pressure differential; absolute pressure; cleaning and lining, if performed; average amount of traffic traversing pipe in a 24-hour period; percent of length in low, moderate, or highly corrosive soil; and number of freezes and thaws since installation.

In addition, census tract data were collected to analyze the effect of surface development and land use on pipe breakage. These data are as follows: percentage in transportation, percentage in industry, percentage in commerce, percentage in residences, and population density.

Soil data were obtained from U.S. Soil Conservation Service maps, and pipe locations were plotted to determine surrounding soil type. The Soil Conservation Service provided the criteria for evaluating soil corrosivity, and determination was made as to whether or not the pipes lay in high, moderate, or low corrosive soil.

Most of the water works pipes are beneath city streets; only a few are installed beneath sidewalks. Traffic data were collected from both county and city data sources. Because most of the street pavement in the utility service area is uniform, stress upon the mains is due primarily to overhead traffic, not to differences in road surfaces. Traffic is monitored only at intersections; therefore, data were not available for most of the intersections in the data base.

Weather information obtained from the U.S. Weather Bureau was complete. Data from appropriate regional planning commissions was the source of land use data for transportation, residential, commercial, and industrial activities for each census tract in the large utility's service area.

With the use of these data, a series of analyses were made incorporating: survival analysis, probability of maintenance event, maintenance event equations, economic analysis of replacement, and the impact of water quality on failure rate.

Survival Analysis.—A study was made of repairs to all pipes in the data base from the first through the tenth repair. Repair mortality curves (Fig. 1) show that, over a period of 40 years, 52.5% of the pipes studied have had no maintenance events, 48% had one maintenance event, 30% had two maintenance events, etc. These data indicate that a minority of pipes are responsible for a majority of the maintenance events. As will be seen in the following section, those pipes that had maintenance events, had them at an increasing frequency over time.

It was also possible to develop the life expectancy of pipes based on their age (8). Five-year-old mains with no maintenance events can expect to have an additional 11.2 years without an event, while 30-year-old mains, have 5.7 years, and 40-year-old mains, have 1 year remaining (Fig. 2).

Probability of Failure.—Of the pipes studied, only a relatively small number experience maintenance events, even after long periods of time. For those that did experience such events, the time between one event and the next became increasingly short (Fig. 3). To study this phenomenon, the interarrival time between repairs was formulated as an exponential function. Fig. 4 shows the probability of a failure occurring at time t equal or less than time T, given that a previous break has occurred (2). For instance, the probability that a pipe will experience a second maintenance event given that it has experienced a previous

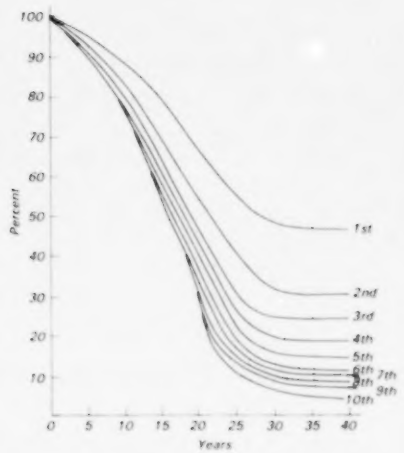

FIG. 1.—Percent Having *n* Repair Events

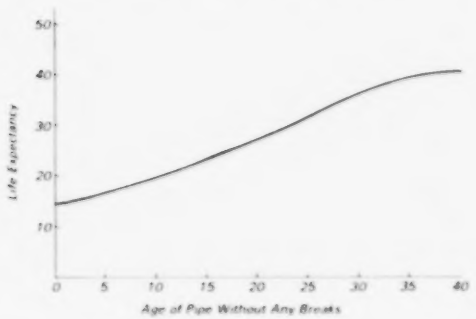

FIG. 2.—Life Expectancy of Pipes

break in less than 15 years is approx 0.40 (Fig. 4). The relative slopes of the curves indicate that the time between a failure becomes increasingly short as the number of maintenance events increases. For instance, given that a pipe has three events, the probability of having another event in a very short time is high.

Repair records were available after 1940 on 307 pipes considered in the original data set. Because the first maintenance event did not usually occur until 15 years after the pipe has been laid, the analysis could begin at 1930 instead of 1940 on the assumption that no breaks occurred in the first 10 years. Of the 307 pipes laid between 1930 and 1980, only 108 have been repaired.

Examination of the data revealed that two underlying mechanisms seemed to be occurring with those pipes that experienced maintenance events. A lag period occurred between the time the pipe was laid and the first maintenance event.

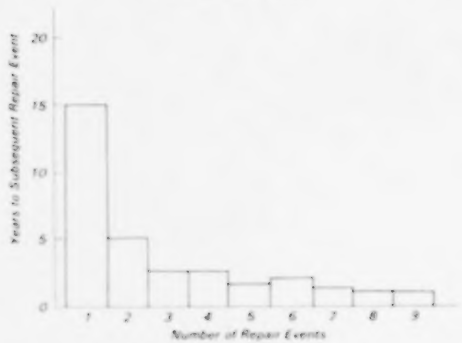

FIG. 3.—Average Number of Years to Subsequent Failure

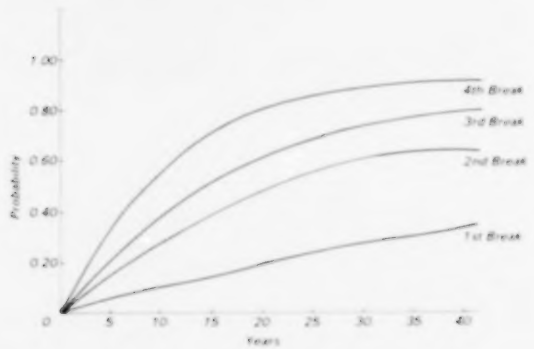

FIG. 4.—Probability of Pipe Failure

After the first event, the number of events seemed to increase exponentially. Therefore, two equations were developed: the first to estimate the time to the first event and the second to estimate the number of events occurring after the first event. These equations are given in the following sections.

First Event Equation

Eq. 1 represents the combined set of data:

$$NY = 4.13 + 0.338D - 0.022P - 0.265I - 0.0983RES - 0.0003LH + 13.28T \quad R^2 = 0.23 \quad \ldots\ldots (1)$$

in which NY = number of years from installation to first repair; D = diameter of pipe, in inches; P = absolute pressure within a pipe; in pounds per square inch; I = percent of pipe overlain by industrial development in a census tract; RES = percent of pipe overlain by residential development in a census tract; LH

= length of pipe in highly corrosive soil; and T = pipe type (1 = metallic; 0 = reinforced concrete).

Accumulated Event Equation

$$REP = (0.1721)\,(e^{0.7197})^{T}\,(e^{0.0044})^{PRD}\,(e^{0.0865})^{A}\,(e^{0.0121})^{DEV}\,(SL)^{0.014}\,(SH)^{0.069};$$

$$R^2 = 0.47 \quad \ldots\ldots\ldots\

be constant over-time, then cost of repair in a given length of pipe in the future year t is

$$C_m(t) = C_b N(t) = C_b K e^{GR(t-t_o)} \quad \ldots\ldots (4)$$

If the present year is denoted by t_p, and the (noninflationary) discount rate is R, then present value of this maintenance cost is simply

$$\frac{C_m(t)}{(1+R)^{t-t_p}} \quad \ldots\ldots (5)$$

Denote t_r as the year in which the pipe will be replaced. The present value of maintenance cost from the present year t_p to the year t_r is

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{t-t_p}} \quad \ldots\ldots (6)$$

substituting Eq. 4 into Eq. 6 yields

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_b K e^{GR(t-t_o)}}{(1+R)^{t-t_p}} \quad \ldots\ldots (7)$$

If the new pipe will not have any new events, then $P_m(t_r)$ represents all future maintenance costs. Other cases will be examined later.

The cost of replacing a pipe, expressed in the same constant dollars as C_b, is C_r. The present value in year t_p of replacing a pipe in year t_r is, therefore

$$P_r(t_r) = \frac{C_r}{(1+R)^{t_r-t_p}} \quad \ldots\ldots (8)$$

$P_m(t_r)$ is an increasing function of t_r because, for every additional year that passes before the pipe is replaced, there is an additional term in Eq. 8. On the other hand, $P_r(t_r)$ decreases with t_r because C_r is assumed to be constant, whereas the denominator increases with t_r.

The optimal timing for replacement is that for which the total cost

$$P_t(t_r) = P_m(t_r) + P_r(t_r) = \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{t-t_p}} + \frac{C_r}{(1+R)^{t_r-t_p}} \quad \ldots\ldots (9)$$

is a minimum. Therefore, it is important to find the value to t_r, which minimizes Eq. 9, i.e.

$$\operatorname{Min}_{t_r}[P_t(t_r)] = \operatorname{Min}_{t_r}\left[\sum_{t=t_p}^{t_r} \frac{C_b K e^{GR(t-t_o)}}{(1+R)^{t-t_p}} + \frac{C_r}{(1+R)^{t_r-t_p}}\right] \quad \ldots\ldots (10)$$

Differentiating with respect to t_r, setting Eq. 10 to zero, and solving for t_r yields the optimal value:

$$t_r = t_o + \frac{1}{GR} \ln\left[\frac{\ln(1+R)C_r}{KC_b}\right] \quad \ldots\ldots (11)$$

Eq. 11 can be used to estimate the optimal replacement time for a given length of pipe. Eq. 1 can be used to estimate t_o, and data from Eq. 2 can be used to

estimate K and GR. Table 2 contains typical values from the data base used to estimate the parameters in Eq. 11.

The value for NY in Eq. 1 is t_o in Eq. 3. The constant in the fourth term of Eq. 2 is GR, and the rest of the terms are calculated for K in Eq. 3. Eq. 3 can be rewritten:

$$REP = 1.1560\, e^{0.0865(t-17)} \quad \ldots\ldots\ldots\

spent on repair exceeds the amortized value of the main in the ground. A cost trade-off can be calculated by taking the actual historic cost of laying a main, updating it to present value by use of the construction cost index; amortizing the cost by the formula

$$V = (CM)\frac{i(1+i)^y}{(1+i)^y - 1} \quad \ldots\ldots\ldots\

Influence of Water Quality.—Water quality may also affect repair and replacement costs in water distribution systems, e.g., corrosive water may increase the number of breaks in water systems. Analyzing the effects of water quality within a single utility is difficult because water quality is generally uniform throughout the system (9).

The corrosivity of drinking water is a parameter that has health and economic significance as well as aesthetic significance. Corrosion in a distribution system may add contaminants to finished water before it reaches the consumer. Some of these contaminants, such as lead and cadmium, at sufficiently high concentration levels in drinking water, may constitute a health hazard.

The annual loss from water corrosiveness has been estimated at about $700 million (3,4,5). In addition to the deterioration of the pipe used to convey water, water leakage from deteriorated distribution systems can be substantial. In some instances, as much as 25% of the water leaving a treatment plant is lost before reaching the consumer.

To analyze the effects of corrosion on water loss and cost of water supply, a sample of water utilities throughout the United States (60 in this case) was selected, and the hardness or softness of the water was determined. For the purpose of this analysis, if the raw water contained less than 60 mg/L of hardness as $CaCO_3$, it was considered soft. Utilities that altered their source water by treatment were placed in the appropriate category (hard or soft).

The analysis showed utilities with soft water had significantly higher total unit costs than those with less aggressive water. In fact, based on the following equation, unit costs should be 31% higher:

$$TUC = 460.96 + 205.73\,W; \quad R^2 = 0.07 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

in which TUC = unit cost, in dollars per millions of gallons; and W = water quality (1 = aggressive; 0 = nonaggressive).

Obviously, the cost relationships associated with pipe failure and corrosion are much more complicated that the simple relationship shown in Eq. 14. Although the R^2 is small, the results are significant at the 0.05 level.

Another factor associated with corrosion is water loss. The following equation was developed based on the loss of revenue producing water as compared to the total water treated:

$$L = 0.0996 + 0.0804W + 0.001547FA - 0.0565S - 0.000029ELD;$$

$$R^2 = 0.0337 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

in which L = loss percentage; W = water quality (1 = aggressive; 0 = nonaggressive); FA = age of first pipe; S = source (0 = ground; 1 = surface); and ELD = elevation difference.

Some of the signs of the coefficients in Eq. 15 appear counterintuitive. Based on Eq. 15, however, utilities with small differences in elevation suffer significantly greater water loss. This loss could be because of a lack of pressure zones. Pressure zones are essential to ensure adequate water service in systems with hills; they allow pipes within these zones to be of similar internal pressure. The pipes in systems in generally flat terrains having only one pressure zone are subjected to varying pressure, have increased breakage, and a significantly

greater percent of loss. Surface supplies also have a lower loss rate than do ground-water supplies. This may be because most ground-water supplies pump directly to the customer, and, therefore, have higher pressure differentials than do systems that incorporate a large number of pressure zones with tanks and standpipes.

Although the R^2 are low, the variables in Eqs. 14 and 15 are significant. Therefore, cross-sectional analysis in this study indicates that aggressive water is a factor, along with many others, in the cost of water supply. Although not conclusive, the results seem to justify more detailed case control studies of systems supplying either aggressive or nonaggressive water.

Summary and Conclusions

This report has dealt with problems associated with maintaining and replacing water supply distribution systems. Statistical models as well as graphic displays have been developed to examine the relationships between water supply infrastructure development and population distribution and growth. A technical economic analysis of the factors influencing the reliability of a water distribution system and associated costs for repair and replacement was made. The effects of water quality (corrosivity) on water loss and system cost was also examined.

Several conclusions can be drawn from the development of the equations for maintenance events:

1. Metallic pipes take nearly 13 years more to experience maintenance problems than do reinforced concrete pipe. Metallic pipes accumulate more maintenance events than do reinforced concrete pipes over a period of time.
2. Large diameter pipes tend to have a longer period before the first maintenance event than do smaller diameter pipes.
3. Large percentages of industrial development decrease time until the first maintenance event.
4. Amount of development increases repeat breaks.

The equations should not be used for predictive analysis, but can be used to indicate some of the variables which accelerate or retard maintenance events. Using these equations, it was possible to develop a scenario for the time of optimal repair and replacement. For the data used in this analysis, the optimal repair period was slightly over 30 years.

Water quality may have an adverse impact on the maintenance event frequency for water delivery system pipes. Analysis revealed that utilities with aggressive water might expect up to 31% higher unit costs.

Throughout the various analyses, difficulties were encountered in the data collection. In many cases, the format for recording data was left up to various individuals throughout the years, and was, therefore, subject to much individual discretion. Most technical data obtained from agencies, such as the National Weather Service or Soil Conservation Service were good; however, data from the utilities and planning agencies sometimes lacked consistency and completeness.

One conclusion to be drawn from this study is the need for water utility managers to institute careful record keeping procedures for tracking pipe repair and

replacement costs. Significant savings can be achieved by replacing transmission and distribution pipes at the proper time. The issue of a system deterioration will no doubt become much more significant in the future.

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Appendix II.—Notation

The following symbols are used in this paper:

PD = population density, in people per acre;
PVA = pipe volume/acre, in cubic ft per acre;
AY = age of pipe, in years;
$CFBD$ = distance from CBD, in miles;
NY = number of years from installation to first repair;
D = diameter of pipe, in inches;
P = absolute pressure within a pipe, in pounds per square inch;
I = percent of pipe overlain by industrial development in a census tract;
LH = length of pipe in highly corrosive soil;

T = pipe type (1 = metallic; 0 = reinforced concrete);
REP = number of repairs;
RPD = pressure differential, in pounds per square inch;
A = age of pipe from first break;
DEV = percent of land over pipe in low and moderately corrosive soil;
SL = surface area of pipe in highly corrosive soil;
SH = surface area of pipe in highly corrosive soil;
$N(t)$ = number of maintenance events in a given section of pipe;
K = constant resulting from the parameter values in Eq. 4.
t = number in years from installation;
to = number of years from installation to the first maintenance event;
GR = growth rate cofficient (dimension is one per year);
V = value;
CM = cost of the pipe replacement in 1978 dollars;
i = interest rate;
y = year;
TUC = unit cost, in dollars per millions of gallons;
W = water quality (1 = aggressive; 0 = nonaggressive);
L = loss percentage;
W = water quality (1 = aggressive; 0 = nonaggressive);
FA = age of first pipe;
S = source (0 = ground; 1 = surface); and
ELD = elevation difference.

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